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Research Article

Battling the Cabbage Butterfly: A Comparative Analysis of Organic and Chemical Control Methods

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ABSTRACT

The cabbage butterfly (*Pieris brassicae*) is a major lepidopteran pest of cruciferous vegetables, causing significant yield losses, especially during its larval stages. In light of increasing concerns about synthetic pesticide resistance, environmental hazards, and non-target effects, the current study was conducted to evaluate and compare the efficacy of selected botanical extracts and chemical insecticides against different larval instars of *P. brassicae* under controlled laboratory conditions. Three organic treatments neem (*Azadirachta indica*), garlic (*Allium sativum*), and cannabis (*Cannabis sativa*) extracts were prepared in aqueous form and tested at three concentrations (10%, 20%, and 30%). Two commonly used synthetic insecticides bifenthrin (10% EC) and lambda-cyhalothrin (2.5% EC) were evaluated at three dose levels: the Field Recommended Dose (FD), one-tenth (FD/10), and one-hundredth (FD/100) of FD. A leaf-dip bioassay method was used in which treated cabbage leaf discs were exposed to third, fourth, and fifth instar larvae of *P. brassicae*. The results revealed that both chemical insecticides demonstrated significantly higher mortality rates than the botanical extracts. At the field dose, lambda-cyhalothrin and bifenthrin caused over 80% mortality in all instars, with nearly 90% mortality in third instars. Among botanical extracts, neem exhibited the highest efficacy, particularly at 30% concentration, causing up to 76.6% mortality in third instar larvae. Garlic showed moderate efficacy, while cannabis extract was the least effective, especially against older instars. Larval susceptibility was inversely related to developmental stage, with third instars being significantly more vulnerable than fourth and fifth instars across all treatments. These findings suggest that neem extract has strong potential as a biopesticide and could be effectively integrated into pest management strategies to reduce reliance on chemical insecticides. The study highlights the importance of early intervention and supports the incorporation of botanical extracts into sustainable and environmentally responsible integrated pest management (IPM) programs for cruciferous crops.

Keywords: Biopesticide, Cabbage Butterfly, Chemical Insecticides, Garlic, Neem.

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INTRODUCTION

The cabbage butterfly, *Pieris brassicae* (Linnaeus), is recognized globally as a serious pest of cruciferous vegetables, including cabbage, cauliflower, broccoli, kale, and Brussels sprouts. This pest is widespread across Europe, Asia, and parts of North Africa, with its range expanding due to climate change and globalization of agricultural trade (Mpumi et al., 2020). In its larval stage, the cabbage butterfly inflicts significant damage to the host plants, feeding on leaves and young shoots, resulting in severe defoliation. The presence of this pest has long been a challenge for sustainable agriculture due to its capacity for rapid population growth, high mobility and multivoltinism, allowing it to complete multiple generations in a single cropping season (Saisri et al., 2022).

The damage caused by the cabbage butterfly is most severe during the larval stage, when the caterpillars consume large quantities of leaf tissue. The larvae are gregarious feeders in their early stages and can skeletonize leaves within a short period, reducing the photosynthetic capacity of the plant and ultimately leading to stunted growth and reduced yield (Kumaranag et al., 2014). In crops such as cabbage and cauliflower, which are grown for their leafy or compact head structures, such damage results in both qualitative and quantitative losses. Infestations may also render the produce unmarketable due to physical blemishes and contamination with larval frass. In addition to direct feeding damage, the pest opens up pathways for secondary infections caused by bacterial and fungal pathogens, which can exacerbate crop loss (Kingsolver, 2000).

Globally, *Pieris brassicae* is considered a key pest in cruciferous vegetable farming systems. Studies conducted in Europe and Asia have shown that uncontrolled infestations can result in yield losses of 30% to 80%, depending on crop variety, environmental conditions, and control measures adopted. In intensive vegetable farming areas, especially where monoculture systems dominate, the pest pressure is typically higher (Subedi et al., 2024). In Pakistan, this pest is particularly problematic in the plains of Punjab, parts of Sindh, and the hilly terrains of Khyber Pakhtunkhwa and Azad Jammu and Kashmir (Imran et al., 2017). Surveys and field observations in these regions consistently report high infestation levels during both spring and autumn growing seasons, with damage percentages often exceeding 50% in untreated or poorly managed fields (Hussain et al., 2022).

The growing concern over pesticide residues, insecticide resistance, and non-target effects has shifted attention toward safer and more sustainable pest management options. Organic control strategies have become increasingly important, especially in ecological and organic farming systems (Punniyakotti et al., 2024). Among these, the use of botanical extracts derived from indigenous plants has been a promising avenue. Neem (*Azadirachta indica*), for instance, contains several biologically active compounds such as azadirachtin and nimbin that function as insect growth regulators and feeding deterrents (Nisbet, 2000). Numerous field and laboratory studies have shown neem extract to be effective in reducing larval populations and oviposition rates of *P. brassicae*. Its use has the added benefit of being biodegradable and safe for pollinators and other beneficial insects (Seljåsen and Meadow, 2006).

Garlic (*Allium sativum*) extract is another botanical formulation widely studied for pest control due to its sulfur-containing compounds like allicin, which possess strong repellent and antifeedant properties. Application of garlic extract on cruciferous crops has been associated with reduced larval feeding and lower pest survival rates (Golubkina et al., 2022). Similarly, extracts from *Cannabis sativa* have emerged as novel bio-rational tools for insect pest management. Cannabis contains a range of bioactive compounds including cannabinoids and terpenoids, some of which have been observed to interfere with insect neurological functions and digestion. Though cannabis is less commonly studied in the context of vegetable pest control, early experimental evidence indicates its potential role in suppressing lepidopteran larval development (Prvulović et al., 2023).

Despite these advancements in organic pest control, chemical insecticides continue to be the primary tool for pest management in most conventional farming systems due to their immediate knockdown effect and ease of application (Baker et al., 2020). Among synthetic insecticides, bifenthrin and lambda-cyhalothrin have been widely used for controlling lepidopteran pests, including the cabbage butterfly (Khan et al., 2017). Bifenthrin, a synthetic pyrethroid, acts on the sodium channels of insect nerve cells, causing paralysis and eventual death. It is favored for its residual activity and effectiveness against a broad range of pests. Lambda-cyhalothrin, another potent pyrethroid, also targets the insect nervous system, leading to rapid pest mortality. Its systemic and contact actions make it effective in managing sudden outbreaks, particularly during peak larval infestations (Bhardwaj et al., 2020).

However, the frequent and often indiscriminate use of these chemical insecticides has led to several issues, including the development of resistance in pest populations, environmental contamination, and harmful effects on non-target organisms, including natural enemies and pollinators. Therefore, there is a pressing need to develop and promote integrated pest management strategies that combine both chemical and organic methods in a complementary fashion. Such integrated approaches can provide effective control of the cabbage butterfly while minimizing the ecological and health risks associated with chemical pesticides (Siddiqui et al., 2023).

Given this context, the present study was conducted to evaluate and compare the efficacy of selected organic and chemical methods for the control of the cabbage butterfly, *Pieris brassicae*, under laboratory conditions. Specifically, the research aimed to assess the insecticidal potential of neem, garlic, and cannabis plant extracts, alongside bifenthrin and lambda-cyhalothrin, in reducing larval populations and minimizing crop damage in cabbage fields. By comparing the effectiveness of these organic and synthetic approaches, the study sought to determine their relative performance in suppressing pest populations and protecting crop yield. The ultimate goal was to generate data that could contribute to the formulation of an integrated pest management strategy for cabbage growers, one that balanced efficacy, environmental safety, and sustainability. Through this work, practical recommendations were developed for the sustainable control of the cabbage butterfly, thereby supporting environmentally responsible vegetable production systems.

MATERIALS AND METHODS

Insect collection and rearing

The present study was conducted under controlled laboratory conditions. Larvae of the cabbage butterfly (*Pieris brassicae*) were collected from infested cabbage fields in the local area. The collected larvae were reared on fresh cabbage leaves free from any pesticide residue. The rearing was carried out in plastic containers under standard laboratory conditions maintained at 25 ± 2°C temperature, 65 ± 5% relative humidity, and a 16:8 hour light:dark photoperiod until the larvae reached the third instar stage, which were used in the bioassays.

Preparation of plant extracts for organic treatments

To evaluate the efficacy of botanical treatments against *Pieris brassicae* larvae, three different plant species known for their insecticidal properties were selected for the preparation of aqueous extracts. These included neem leaves (*Azadirachta indica*), garlic cloves (*Allium sativum*), and cannabis leaves (*Cannabis sativa*). The plant materials were collected from ecologically clean, pesticide-free agricultural or wild areas to ensure that the bioactive compounds were not degraded or contaminated. Upon collection, all plant materials were inspected for freshness and quality, and only healthy, undamaged samples were selected for use.

The collected plant materials were first thoroughly washed under running tap water followed by a final rinse with distilled water to remove any adhering soil particles, dust, or microbial contaminants. After cleaning, the materials were spread in a single layer on clean, dry trays and allowed to dry in the shade at ambient room temperature (approximately 25°C) for 24 hours. This gentle drying process was essential to reduce surface moisture while preserving the integrity and efficacy of thermolabile secondary metabolites such as alkaloids, flavonoids, terpenoids, and sulfur-containing compounds, which are often responsible for insecticidal activity.

Once dried, 100 grams of each plant material were weighed separately using an electronic balance and subjected to mechanical maceration. For this purpose, a high-speed mechanical blender was used to crush the plant material into a fine paste. During the blending process, 200 mL of distilled water was gradually added to facilitate the breakdown of plant tissues and promote the release of active compounds into the solution. The homogenate formed was then subjected to a two-step filtration process. Initially, the mixture was passed through a double-layered muslin cloth to eliminate coarse plant debris. The resulting filtrate was subsequently filtered through Whatman No. 1 filter paper under vacuum to yield a clear aqueous extract free of particulates.

The obtained filtrates were stored temporarily at 4°C and used to prepare three working concentrations: 10%, 20%, and 30% (v/v). These concentrations were made by diluting the stock extracts with distilled water in appropriate proportions to standardize the volume and maintain consistency across all experimental replications. The freshly prepared solutions were stored in sterile, airtight glass containers at 4°C to minimize microbial growth and chemical degradation, and were used within 48 hours of preparation to ensure maximal biological activity.

For control treatments, distilled water alone was used without any plant extract. This control allowed for direct comparison of larval mortality and ensured that any observed effects could be attributed solely to the bioactivity of the plant extracts.

Chemical control treatments

Two synthetic insecticides commonly used against lepidopteran pests were selected for chemical control treatments: bifenthrin (10% EC) and lambda-cyhalothrin (2.5% EC). Each insecticide was tested at three dose levels: the Field Recommended Dose (FD), one-tenth of the field dose (FD/10), and one-hundredth of the field dose (FD/100). These concentrations were prepared by diluting the commercial formulations with distilled water according to the manufacturer’s recommendations. Distilled water alone was used as the control for chemical treatments.

Bioassay procedure using leaf-dip method

To assess the insecticidal potential of both organic and chemical treatments against *Pieris brassicae* larvae, a standardized leaf-dip bioassay technique was employed. Fresh, healthy cabbage leaves were harvested from pesticide-free plants and thoroughly rinsed with distilled water to eliminate any surface contaminants. These leaves were then cut into uniform circular discs, each approximately 9 cm in diameter, to match the size of the Petri dishes used in the experiment. This standardization ensured equal exposure surface area across all treatments.

Each leaf disc was immersed individually in its respective treatment solution whether organic extract or chemical insecticide for 10 seconds. During immersion, care was taken to ensure that both the upper and lower surfaces of the leaves were fully covered by the solution, maximizing the contact area for potential ingestion or absorption of toxic compounds by the larvae. After treatment, the leaf discs were carefully removed from the solutions and placed on sterile filter paper at ambient room temperature. They were allowed to air-dry for approximately 30 minutes to allow evaporation of any excess solution and to ensure that only the residue remained on the leaf surface, thereby simulating field conditions.

Once dried, the treated cabbage discs were transferred into clean, sterile Petri dishes (9 cm in diameter), each lined with a moistened filter paper to maintain optimal humidity within the micro-environment of the dish. This moisture helped prevent the leaf disc from wilting and ensured larval activity remained unaffected by dehydration stress. The bioassay was conducted under strictly controlled laboratory conditions, maintained at 25 ± 2°C temperature, relative humidity of 65 ± 5%, and a photoperiod of 16:8 hours light to dark cycle, simulating natural day-night conditions conducive to larval activity.

Larval exposure and experimental design

In order to comprehensively evaluate the treatment efficacy across different developmental stages, larvae of three instars third, fourth, and fifth of *P. brassicae* were used in the bioassay. These instars were selected to understand stage-specific susceptibility to both organic and chemical interventions. For each treatment concentration, ten larvae from each instar group were carefully selected and gently transferred into the treated Petri dishes using a fine camel hairbrush to avoid physical injury or stress to the larvae.

Each instar-treatment combination, whether organic (with concentrations of 10%, 20%, and 30%) or chemical (Field Recommended Dose, FD/10, FD/100), was replicated three times to ensure statistical validity and minimize random error. This experimental design yielded a total of 30 larvae per concentration per instar, allowing robust comparative analysis across all treatments and stages.

After the larvae were introduced, the Petri dishes were sealed with parafilm to prevent larval escape and desiccation while allowing for air exchange. The dishes were then placed in an incubator set to the previously mentioned controlled environmental conditions. These standardized conditions were maintained throughout the 24-hour exposure period to ensure that any observed mortality could be attributed solely to the treatment effects rather than external environmental stressors.

Mortality assessment and data analysis

Larval mortality was assessed 24 hours following the application of treatments. Mortality was determined based on the absence of any movement when larvae were gently prodded with a fine camel hairbrush. Only percentage mortality data were recorded for each treatment group. In cases where mortality was also observed in the control group, the data were corrected using Abbott's formula to account for natural mortality and ensure accurate efficacy estimation. The corrected percentage mortality data were subjected to statistical analysis using one-way Analysis of Variance (ANOVA) to determine the significance of differences among treatments. All statistical analyses were conducted using standard statistical software, and treatment means were separated using appropriate post hoc tests where applicable.

RESULTS AND DISCUSSION

The comparative efficacy of organic and chemical treatments against *Pieris brassicae* larvae was evaluated by recording percentage mortality 24 hours after treatment application. The study revealed that both organic extracts and chemical insecticides exhibited substantial larvicidal effects, with varying degrees of effectiveness depending on larval instar and concentration. Notably, earlier larval stages (third instar) were more susceptible to both organic and chemical interventions, while the efficacy generally declined in older larvae (fourth and fifth instars).

Mortality response to neem leaf extract

The larvicidal potential of neem (*Azadirachta indica)* extract at three different concentrations (10%, 20%, and 30%), a clear dose-dependent relationship was observed, with mortality rates increasing in proportion to extract concentration. At the highest concentration (30%), neem extract caused 76.6% mortality in third instar larvae, followed by 56.6% and 60% mortality in fourth and fifth instars, respectively. This trend underscores neem's effectiveness as a potent botanical insecticide, particularly against early larval stages (Figure 1).

The 20% concentration of neem still showed promising results, inducing 63.33% mortality in third instar, 53.3% in fourth instar, and 50.0% in fifth instar larvae. The lowest concentration (10%) exhibited a milder effect. The results suggest that neem extract contains strong insecticidal properties that are likely due to the presence of azadirachtin and other limonoids, which act as antifeedants and growth regulators. Moreover, the progressive decrease in mortality with larval development indicates that younger larvae are more vulnerable to the bioactive compounds, possibly due to thinner cuticle layers and greater feeding activity (Figure 1).

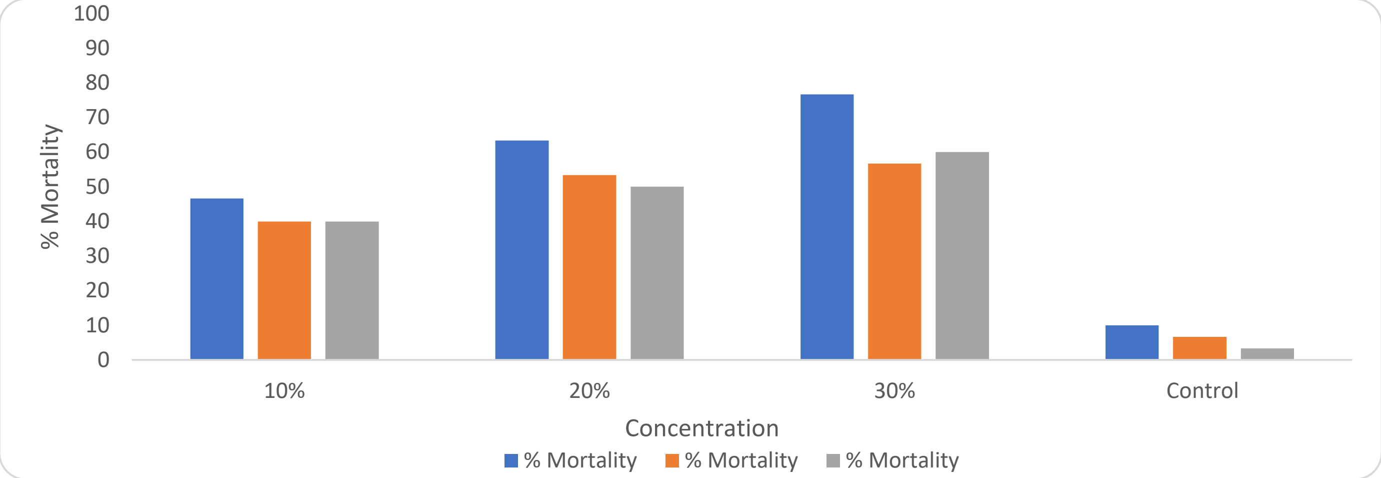

Figure 1. Percentage mortality of 3rd, 4th, and 5th instar larvae of cabbage butterfly at different concentrations (10%, 20%, 30%) of neem leaf extract.

Mortality response to garlic extract

The mortality rates of larvae treated with garlic (*Allium sativum*) extract also exhibited a concentration-dependent increase in larval mortality, although to a slightly lesser extent. At 30% concentration, garlic extract caused 46.6% mortality in third instar, 50.0% in fourth, and 53.3% in fifth instar larvae (Fig. 2). The 20% garlic extract concentration showed 53.3% mortality in third instar, decreasing to 46.6% and 43.3% in fourth and fifth instars. At the lowest dose (10%), mortality was notably lower 36.6%, 23.3%, and 26.66% for the respective instars. Although garlic is generally known for its repellent properties due to sulfur compounds such as allicin, its contact and ingestion toxicity appear to be less pronounced than neem (Figure 2).

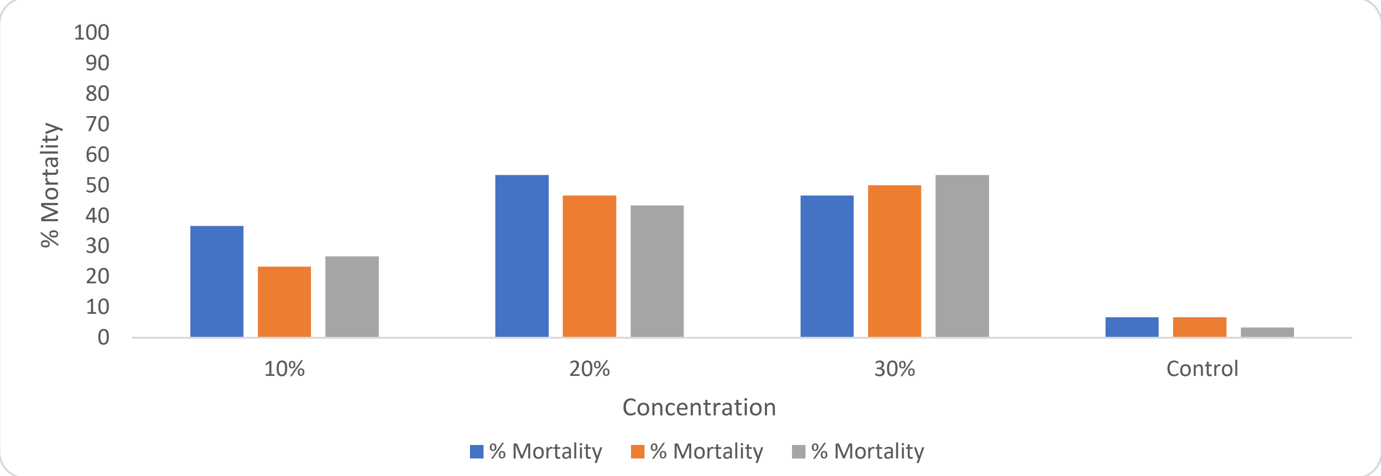

Figure 2. Percentage mortality of 3rd, 4th, and 5th instar larvae of cabbage butterfly at different concentrations (10%, 20%, 30%) of Garlic extract.

Mortality response to cannabis leaf extract

The results of cannabis (*Cannabis sativa*) leaf extract on larval mortality revealed that, among the three botanical treatments, cannabis extract showed the lowest efficacy. However, it still demonstrated statistically relevant larvicidal activity, particularly at higher concentrations. At 30%, cannabis induced 30.0% mortality in third instar, 33.3% in fourth, and 23.3% in fifth instar larvae. Mortality declined with decreasing concentrations: at 20%, cannabis extract caused 36.6%, 26.6%, and 16.6% mortality in third, fourth, and fifth instars, respectively. The 10% concentration resulted in the lowest mortality levels, with 33.3%, 16.6%, and 6.6% for third, fourth, and fifth instars. Although not as potent as neem or garlic, the cannabis extract still showed potential larvicidal properties, likely due to the presence of phytochemicals such as terpenoids and cannabinoids, which may interfere with insect neuromuscular coordination (Figure 3).

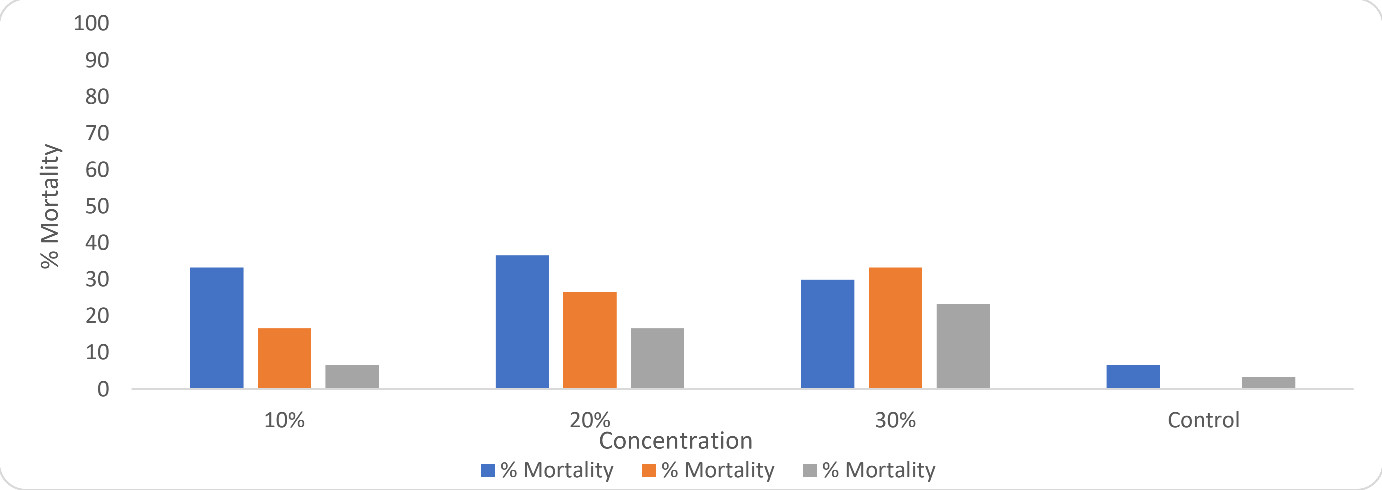

Figure 3. Percentage mortality of 3rd, 4th, and 5th instar larvae of cabbage butterfly at different concentrations (10%, 20%, 30%) of Cannabis extract.

Efficacy of bifenthrin on larval mortality

The larvicidal activity of the synthetic insecticide bifenthrin is shown in Figure 4. Bifenthrin demonstrated exceptional efficacy at the Field Recommended Dose (FD), causing 83.33% mortality in third instar larvae, 76.6% in fourth instar, and 56.6% in fifth instar within 24 hours. This high level of efficacy underscores bifenthrin's effectiveness as a fast-acting neurotoxic insecticide that causes immediate paralysis and death in exposed larvae. Even at FD/10, mortality remained high, especially in younger larvae, with 66.6% in third instar, 50.0% in fourth, and 43.3% in fifth instar larvae. At the lowest dose tested (FD/100), mortality rates were reduced but still significant (Figure 4).

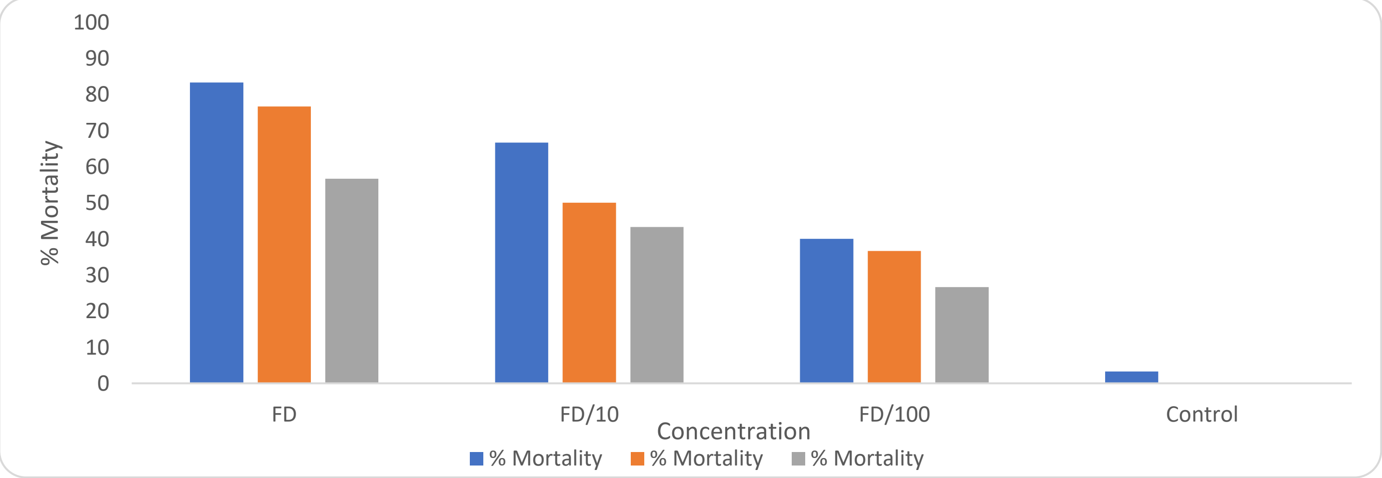

Figure 4. Percentage mortality of 3rd, 4th, and 5th instar larvae of cabbage butterfly at different concentrations (FD, FD/10, FD/100) of Bifinthrin.

Efficacy of lambda-cyhalothrin on larval mortality

Lambda-cyhalothrin showed similar efficacy patterns to bifenthrin. At the full recommended field dose, this insecticide caused 90% mortality in third instar, 80.0% in fourth, and 83.3% in fifth instar larvae. The rapid and high mortality confirms lambda-cyhalothrin's strong neurotoxic action on lepidopteran pests. When applied at FD/10, mortality decreased but remained high 76.6%, 60.0%, and 53.3% for third, fourth, and fifth instars, respectively. At the lowest dose (FD/100), the efficacy further declined to 46.6%, 43.3%, and 33.3%, respectively. These results suggest that lambda-cyhalothrin is slightly high effective than bifenthrin and still provides substantial control, particularly at full strength (Figure 5).

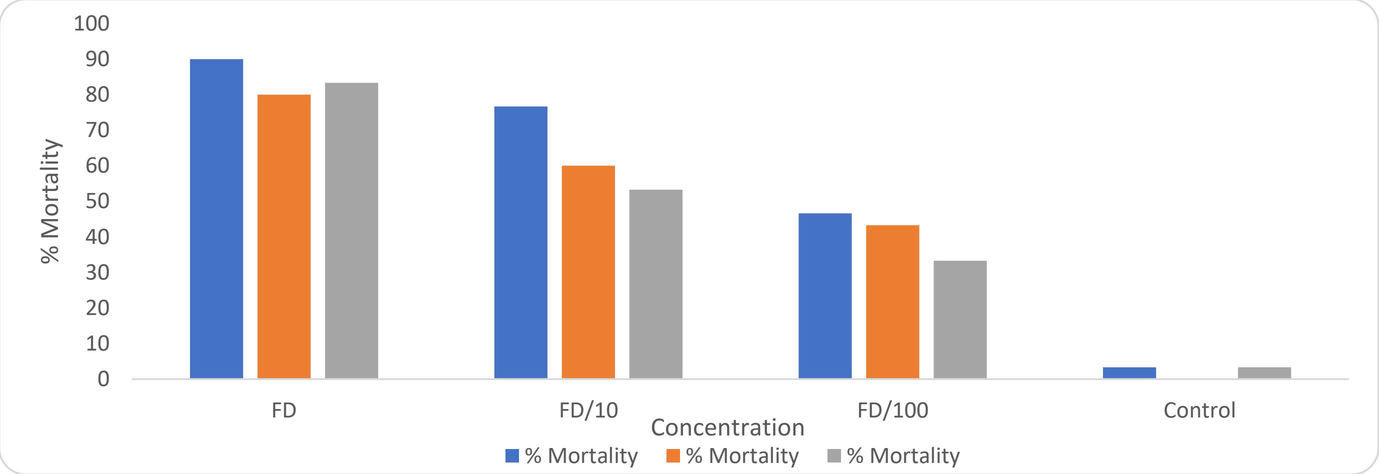

Figure 5. Percentage mortality of 3rd, 4th, and 5th instar larvae of cabbage butterfly at different concentrations (FD, FD/10, FD/100) of lambda-cyhalothrin.

Overall comparison among organic extracts

The comparative analysis of the three organic extracts across different concentrations (Figure 6) revealed that neem consistently outperformed garlic and cannabis in terms of larval mortality across all instars. At 30% concentration, neem induced the highest overall mortality, especially in third instar larvae, making it the most potent organic option in this study. Garlic extract followed neem in efficacy, while cannabis was the least effective, particularly against older instars. The consistent decline in mortality from third to fifth instar larvae across all treatments suggests a stage-specific susceptibility, where early instars are more vulnerable to treatment due to higher metabolic rates and thinner cuticles. These findings emphasize the potential of neem extract as a key component in organic pest control strategies and support the use of botanical insecticides as eco-friendly alternatives or supplements to chemical pesticides, especially within integrated pest management (IPM) frameworks.

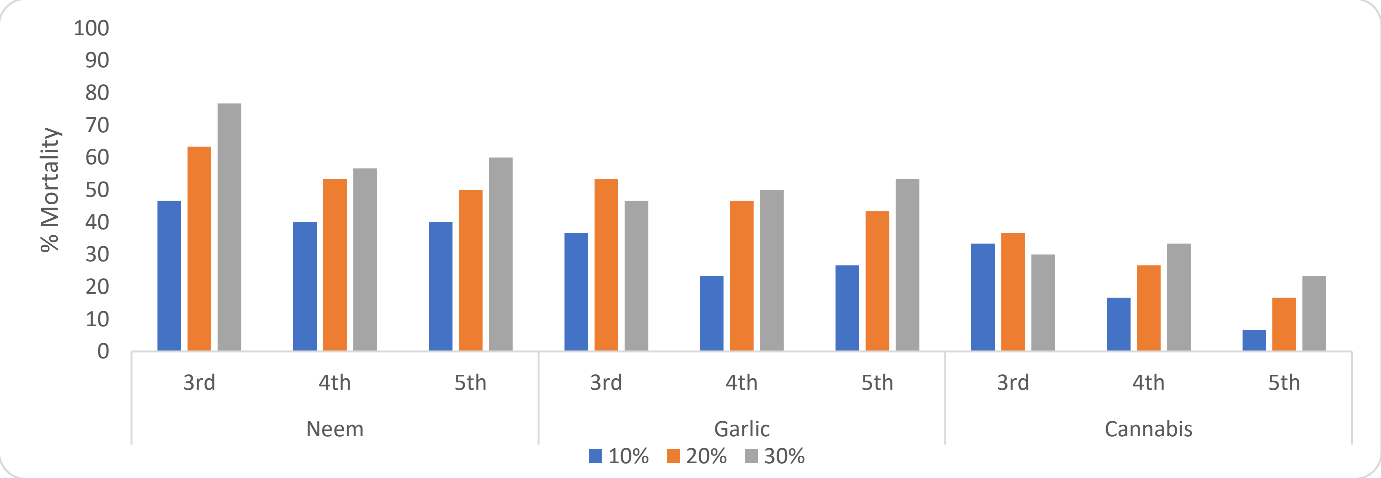

Figure 6. Overall comparison of percentage mortality in 3rd, 4th, and 5th instar larvae of cabbage butterfly treated with neem, garlic, and cannabis extracts at 10%, 20%, and 30% concentration.

The present investigation aimed to assess and compare the larvicidal efficacy of selected organic plant extracts namely neem (*Azadirachta indica*), garlic (*Allium sativum*), and cannabis (*Cannabis sativa*) with synthetic insecticides bifenthrin and lambda-cyhalothrin against different larval instars of the cabbage butterfly (*Pieris brassicae*). The study revealed significant concentration- and stage-specific differences in larval mortality across treatments, with synthetic insecticides generally outperforming botanical extracts. However, neem extract, in particular, showed considerable potential as an effective organic alternative.

Among the botanical treatments, neem extract emerged as the most potent larvicidal agent. It produced mortality rates of over 70% in third instar larvae at the highest concentration tested (30%). These findings are in close agreement with earlier studies that have consistently reported neem as one of the most effective botanical pesticides.

Azadirachtin, the primary active ingredient in neem, has been well documented for its strong antifeedant, growth-inhibiting, and repellent properties. Research by Adusei and Azupio, 2022, emphasized neem's broad-spectrum insecticidal action, including its effectiveness against Lepidopteran pests such as *P. brassicae*. The results of the current study add to this body of evidence, suggesting that neem, particularly at higher concentrations, can significantly reduce larval populations of cabbage butterfly within 24 hours of application.

Garlic extract also demonstrated moderate larvicidal efficacy, with the highest mortality observed in third instar larvae at 30% concentration being slightly over 60%. Though less effective than neem, garlic still showed a consistent trend of increasing mortality with higher concentrations. This is attributed to the presence of sulfur-containing compounds such as allicin and diallyl disulfide, which are known to have insecticidal and deterrent properties. Earlier work by Mamduh et al. (2017) reported garlic's ability to reduce pest activity, feeding, and survival in various insect pests. In the context of this study, garlic's effects were more pronounced in the younger larvae, possibly due to higher feeding rates and less developed cuticular barriers that allowed greater absorption of the toxic compounds.

Cannabis extract, though the least effective among the botanicals, did exhibit measurable larvicidal activity. At the 30% concentration, it caused over 50% mortality in third instar larvae, though its effectiveness declined significantly with older larvae and lower concentrations. The observed insecticidal effect may be linked to the presence of terpenoids and cannabinoids that are known to affect neural and digestive functions in insects.

However, the scarcity of scientific studies on cannabis in entomological research makes it difficult to contextualize its role. While early reports, such as that by Rothschild and Fairbairn (1980), have hinted at the insecticidal potential of certain cannabis-derived compounds, the present study provides a rare empirical dataset supporting its limited efficacy against *P. brassicae*. The lower mortality rates suggest that cannabis may be more suitable for use in pest deterrence or as a component of a broader integrated pest strategy rather than a standalone larvicide (Bhandari and Kumar, 2020).

The chemical insecticides, bifenthrin and lambda-cyhalothrin, predictably caused the highest mortality across all larval instars, particularly at the field recommended dose. Third instar larvae showed nearly 100% mortality under both insecticides, and even the older fourth and fifth instars exhibited mortality rates well above 90% in most cases. These results are consistent with earlier findings, who reported that pyrethroids like bifenthrin and lambda-cyhalothrin have strong contact and ingestion toxicity, rapid knockdown effects, and prolonged residual action against lepidopteran pests (Gajendiran and Abraham, 2018). Their mode of action, which involves disruption of voltage-gated sodium channels in the insect nervous system, leads to paralysis and death within hours of exposure (Ravula and Yenugu, 2021).

Despite their high effectiveness, the continuous and excessive use of such insecticides in conventional agriculture has led to concerns about pest resistance, environmental pollution, and non-target effects, particularly on beneficial arthropods and pollinators. These concerns are increasingly prompting researchers and practitioners to explore safer alternatives and integrate them into sustainable pest management frameworks. The results of this study contribute to that pursuit by demonstrating that neem, and to a lesser extent garlic, can serve as viable substitutes or complements to synthetic chemicals, particularly when applied early in the pest's life cycle.

An important pattern observed across all treatments was the reduced susceptibility of older larval instars (fourth and fifth) compared to the third instar. This suggests a developmental resistance that may stem from physiological and behavioral changes such as thicker cuticle, reduced feeding, or increased detoxification enzyme activity in later larval stages. Similar observations have been showed that early larval instars of *Spodoptera litura* were more vulnerable to botanical and microbial insecticides compared to older ones. This finding underlines the importance of timely intervention in pest control programs, emphasizing that targeting early instar larvae can result in more effective pest suppression with both organic and synthetic tools (Hoesain et al., 2023).

The broader implication of these findings lies in their potential application in integrated pest management (IPM). The use of neem and garlic extracts, either in rotation with or in combination with reduced doses of synthetic insecticides, could offer a practical and environmentally sound approach for managing *P. brassicae* in cruciferous crops. By lowering the frequency and quantity of synthetic insecticide use, such integration could help mitigate the risks associated with resistance buildup and environmental contamination. Moreover, promoting the use of indigenous and readily available botanical resources like neem and garlic supports sustainable agriculture, especially in resource-limited settings.

CONCLUSION

In conclusion, this study provides robust evidence that certain organic treatments, particularly neem extract, are capable of inducing significant mortality in *P. brassicae* larvae under laboratory conditions. While synthetic

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insecticides remain highly effective, their long-term sustainability is questionable due to associated ecological risks. Botanical extracts, though generally slower in action and less potent, offer a safer alternative and can play a crucial role in diversified pest management strategies. Future studies should aim to evaluate the field efficacy of these treatments, explore synergistic combinations, and investigate sublethal and behavioral effects that may contribute to long-term pest suppression.

AUTHOR CONTRIBUTIONS

All authors contributed equally to this research.

COMPETING OF INTEREST

The authors declare no competing interests.

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